SOFTWARE TOOL ARTICLE

**SeqAcademy: an educational pipeline for RNA-Seq and ChIP-Seq analysis [version 2; referees: 1 approved, 1 not approved]**

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**Abstract**

Quantification of gene expression and characterization of gene transcript structures are central problems in molecular biology. RNA sequencing (RNA-Seq) and chromatin immunoprecipitation sequencing (ChIP-Seq) are important methods, but can be cumbersome and difficult for beginners to learn. To teach interested students and scientists how to analyze RNA-Seq and ChIP-Seq data, we present a start-to-finish tutorial for analyzing RNA-Seq and ChIP-Seq data: SeqAcademy (source code: https://github.com/NCBI-Hackathons/seqacademy, webpage: http://www.seqacademy.org/). This user-friendly pipeline, fully written in Jupyter Notebook, emphasizes the use of publicly available RNA-Seq and ChIP-Seq data and strings together popular tools that bridge that gap between raw sequencing reads and biological insight. We demonstrate practical and conceptual considerations for various RNA-Seq and ChIP-Seq analysis steps with a biological use case - a previously published yeast experiment. This work complements existing sophisticated RNA-Seq and ChIP-Seq pipelines designed for advanced users by gently introducing the critical components of RNA-Seq and ChIP-Seq analysis to the novice bioinformatician. In conclusion, this well-documented pipeline will introduce state-of-the-art RNA-Seq and ChIP-Seq analysis tools to beginning bioinformaticians and help facilitate the analysis of the burgeoning amounts of public RNA-Seq and ChIP-Seq data.

**Keywords**

RNA-Seq, ChIP-Seq, alignment, differential gene expression, peak-calling, education, tutorial, pipeline
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Introduction
RNA sequencing (RNA-Seq) is a rapidly expanding technique used to answer broad questions in the life sciences, ranging from mitochondrial function (Mercer et al., 2011) to the pathogenesis of breast cancer (Li et al., 2017). Chromatin immunoprecipitation sequencing (ChIP-Seq) is a genome-wide technique for profiling histone modifications, protein interactions, and transcription factor binding sites (Barski et al., 2007). Using this technique to analyze protein interactions involves very large data sets for computational analysis. The computational steps can identify the locations of features such as DNA-binding enzymes, modified histones, chaperones, nucleosomes, and transcription factors (TFs) (Bailey et al., 2013).

The expanding importance of RNA-Seq and ChIP-Seq data is reflected by its explosive growth in terabytes in the primary public repository for storing this data - the Sequence Read Archive (SRA) (Wheeler et al., 2008). This incredible increase in the amount of public data has not been met with an equal increase in the number of scientists who can skillfully and thoughtfully analyze this important resource. Given the fundamental role that RNA-Seq and ChIP-Seq data, among other next-generation sequencing data types, are likely to play in the coming decades, there is a critical need to teach RNA-Seq and ChIP-Seq analysis to life scientists with diverse interests and backgrounds.

The goal of analyzing RNA-Seq data is often to identify and characterize quantitative differences in gene expression between biological samples from two or more groups. For ChIP-Seq, the goal is to characterize DNA-protein interactions. Biological samples may originate from several different study designs including: different tissue types from the same individual (e.g. cancerous tissue vs. non-cancerous tissue), the same strain of cells under different environmental conditions, or the same tissue under a time-course experiment.

There are major barriers to the novice bioinformatician who is interested in learning how to analyze RNA-Seq and ChIP-Seq data. RNA-Seq and ChIP-Seq data are costly to generate (>$1,000/sample) and cumbersome to store; with data from a single sample often occupying several gigabytes of storage space. However, recent advances, including a greater impetus to deposit sequencing data in SRA ("Principles and Guidelines for Reporting Preclinical Research," 2015) and the innovative alignment of streamed sequencing data (Kim et al., 2015), offer new opportunities to overcome these long-standing problems.

The second barrier to entry is inherent to RNA-Seq and ChIP-Seq data. These datasets are large and complex: there are over 20,000 known genes in the human genome (Naidoo et al., 2011) and the transcriptional diversity of the human genome is not yet fully characterized (Yamashita et al., 2011).

Furthermore, RNA-Seq data is susceptible to “batch effects” and other confounders that can occlude real biological effects or, worse, mislead the un-skeptical researcher. Thus, appropriate analysis of these data requires advanced algorithms and sophisticated statistical methods, coupled with traditional scientific skepticism, to uncover biological insight buried in the data.

These difficulties dissuade many from attempting RNA-Seq and ChIP-Seq analysis, particularly those lacking previous data analysis experience, but the genomics community needs more scientists who can adeptly analyze RNA-Seq and ChIP-Seq data. Moreover, shared understanding of RNA-Seq and ChIP-Seq analysis will produce higher quality discourse between the biologists who are responsible for conducting RNA-Seq and ChIP-Seq experiments and the bioinformaticians who are experts at analyzing the resulting data produced from these experiments. Several well-developed pipelines currently exist for processing RNA-Seq and ChIP-seq data from start to finish (Djebali et al., 2017; Park et al., 2017; Torres-García et al., 2014; Yalamanchili et al., 2017); however, these pipelines are generally designed for advanced bioinformaticians who often have existing practical experience in analyzing high-throughput data. A pipeline designed to teach those with little experience how to analyze high-throughput sequencing data is therefore needed. Thus, we developed a proof-of-concept, well-documented "tutorial pipeline" over the course of a three-day NCBI-sponsored hackathon intended to teach RNA-seq and ChIP-seq analysis to beginners. This tutorial pipeline, “SeqAcademy,” incorporates state-of-the-art RNA-Seq and ChIP-seq analysis tools into a simple, easy to use workflow tutorial and we demonstrate its use with publicly available data.

Methods

Implementation
SeqAcademy uses a self-contained Jupyter Notebook, which runs Python, R, and Bash scripts among others, all from the document itself (Kluvyer et al., 2016). It requires about 16 GB of memory storage. Jupyter Notebook facilitates open science and reproducible code by mixing code chunks with notes and markup. This format, known as “literate programming,” is particularly amenable to teaching bioinformatics because it allows learners to follow along in the document while running each code step directly within the notebook.

Operation
The tutorial begins with an explanation of how to install necessary dependencies and select interesting data from the BioProjects browser. Alignment while streaming the data is done with HISAT2 version 0.1.6 and subsequent quality control with MultiQc version 1.5. The tutorial then splits into two separate protocols: one for RNA-seq, the other for ChIP-seq analysis.
The workflow involved setup, alignment, quality control, analysis, and visualization steps for publicly available RNA-Seq and ChIP-seq data sets. There are many appropriate tools available for each step of RNA-seq and ChIP-seq analysis. Our goal is to present an easy to use and understandable pipeline rather than an exhaustive list of analysis tools. For each step below, we will explain the role of the bioinformatic tool, as well as our rationale for including it in this tutorial pipeline (Figure 1). Here, we present an overview of the steps; further details for each subsection can be found on the project’s Github page.

Setup
The setup step uses the Bioconda channel (Grüning et al., 2017) for the conda package manager to install all of the programmatic dependencies for the entire pipeline. The data sets were selected by searching NCBI BioProject web browser (Barrett et al., 2011). For our use case, we searched for publically available RNA-Seq and ChIP-Seq datasets that were relatively small and thus could be easily downloaded and processed, and would be relatively straightforward to interpret biologically. We therefore selected RNA-Seq and ChIP-Seq data from yeast (Saccharomyces cerevisiae) samples (Mulla et al., 2017; Rawal et al., 2018).

The RNA-Seq data demonstrates the differences in genetic expression between aneuploid and euploid yeast (Mulla et al., 2017). The ChIP-Seq data demonstrates the effects of 3-Amino-1,2,4-triazole (3-AT) on chromatin accessibility (Rawal et al., 2018). We downloaded the reference sequence for Saccharomyces cerevisiae from Ensembl version 84 (RNA-Seq SRA study number: SRP106028 ChIP-Seq SRA study number: SRP132584). We note that the SraRunTables file can be adjusted to specific user data, different from the RNA-Seq or ChIP-seq data sets used in this project. Thus, this lightweight, portable educational pipeline can be adapted to meet the usage needs and interests of a broad base of bioinformatics beginners and teachers.

Alignment
HISAT2 is a software program used for the alignment of raw sequence data, consisting of FASTQ files (Kim et al., 2015). We chose to use HISAT2 because it allows users to stream raw sequence data rather than downloading it to the local machine, reducing disk space and time requirements for users of the SeqAcademy educational tool - an exemplary use of “edge-computing” in bioinformatics. One disadvantage of this approach is that it requires a stable internet connection, as the aligned raw sequence files are downloaded as SAM (sequence alignment mapping) files along with the log files. Nevertheless, by choosing to use HISAT2 for alignment, we reduced required disk space and broadened the potential user base of this pipeline.

RNA-Seq
After alignment and quality control, users convert the SAM files to BAM files with the samtools package version 1.8 (Li et al., 2009). Then, gene expression is quantified with HTSeq version 0.9.1 (Anders et al., 2015). Afterwards, we demonstrate

![Figure 1. Flowchart of the SeqAcademy tutorial.](image-url)
how to extract biological significance from these various analyses, by showing students how to visualize gene expression patterns and undertake exploratory data analysis with principal component analysis (PCA). Finally, we show how to undertake differential expression analysis using DESeq2 version 1.21.0 (Love et al., 2014) and how to visualize these differences with volcano plots and experiment-specific visualizations in the R package ggplot2 version 2.2.1 (Wickham, 2009). Thus, students can learn how to quantify gene expression, answer biologically relevant questions through differential gene expression analysis, and visualize gene expression patterns.

ChIP-Seq

After alignment, we perform peak-calling to determine protein-binding locations in the ChIP-seq data. The peak-calling step of ChIP-Seq involves finding differentially binding sites between the two ChIP-Seq signals (input and immunoprecipitate). Numerous peak callers exist to distinguish biologically relevant signal peak from technical noise for the Chip-Seq experiments. Here, we used the peak-calling algorithm MACS (Model-based Analysis for ChIP-Seq) version 1.4.2 (Zhang et al., 2008). MACS is a commonly used peak-caller and has been shown to have more accurate results than competing peak-callers (Hocking et al., 2017). After calling peaks, the results are sorted and analyzed for intersections using bedtools version 2.27.0, a set of tools for analyzing genomic data (Quinlan & Hall, 2010). Lastly, bedtools output is visualized with Integrative Genomics Viewer (IGV) version 2.4, a genomic data set viewer that allows for visualization of genomic features (Robinson et al., 2011).

Quality control

To generate a quality control report about the success of the alignment, we used MultiQC (Ewels et al., 2016). MultiQC reports the number of reads mapped to one unique location, reads mapped to multiple unique locations, and reads not mapped to any location in the reference genome. MultiQC can provide reports for both RNA-Seq and ChIP-seq data. Reads mapped to one unique location have a higher confidence level of being correctly mapped, as reads mapped to multiple unique locations cannot be localized to the reference with a high degree of probability. While MultiQC is not strictly necessary for this pipeline—the plots and statistics it produces are based off of the HISAT2 alignment summary files - we chose to include it to introduce users to a useful tool that is built for quality control.

Use cases

Target audience

This educational pipeline is designed for students without previous programming experience who are looking for an introduction to the acquisition, processing, analysis, and visualization of either RNA-Seq or ChIP-seq data. Students of next-generation sequencing analysis may range the academic spectrum, from undergraduates to professors, all of whom share an interest in learning to analyze sequencing data. SeqAcademy also offers a useful introduction to the core steps of RNA/ChIP-Seq analysis for use by bioinformatics educators who are teaching a class or mentoring students. Motivated individual learners, for instance a graduate student who is attempting RNA-Seq analysis, may also benefit by working through SeqAcademy. The Jupyter Notebook file is completely self-contained, so users do not need to manage additional input files or tools beyond what is provided directly in the notebook document—every line of code to be run has already been written and tested. Thus, this flexible tutorial may be a suitable introduction to RNA-seq and ChIP-seq analysis for workshops, graduate school classes, or motivated individual learners. We also hope that fellow bioinformatics educators will build off of SeqAcademy to teach intermediate and advanced bioinformatics concepts and skills. The pipeline is simple and modular, so it can easily be adapted to analyze different datasets and customized to meet different user needs.

Learning objectives

The learning objectives of SeqAcademy are two-fold. The first and most immediate or practical objective is for a student to learn how to conduct the core steps of an RNA/ChIP-seq analysis, beginning with a search for publicly available sequencing data and ending with biologically meaningful results. The second objective is to foster a greater understanding of the concepts behind each step. This includes biological reasons behind why certain experiments such as ChIP-Seq and RNA-Seq are run, and the logic behind alignment, differential gene expression, and peak-calling. The tutorial pipeline is purposefully simple, as this will introduce important component of next generation sequencing more gently, and will encourage students to build off of it to create more advanced pipelines that will meet the unique goals of the student.

Table 1 and Table 2 illustrate the sample input yeast data for RNA-Seq and ChIP-Seq, respectively. The RNA-Seq data examines aneuploidy while the ChIP-Seq data shows induction by 3-Amino-1,2,4-triazole (3-AT). Results of the principal component analysis, an unsupervised data reduction technique, of the RNA-Seq data are shown in Figure 2a. The slight clustering of the data into two different groups, euploid and aneuploid can be observed. A volcano plot is used to visualize significant differentially expressed genes between two groups, in this case euploid and aneuploid (Figure 2b). Figure 2c displays the enrichment of chromosome X for differentially expressed genes, consistent with the aneuploid sample having an extra X chromosome. Figure 3 shows an IGV screenshot of how peaks of protein-enrichment are distributed across the yeast genome. The corresponding genes can be examined to determine proteins involved in 3-AT induction.

Conclusion and next steps

Limitations and future directions

There are several limitations to take into account with this tutorial and future directions for further work. In this tutorial, we focused on using RNA-seq on “bulk” or homogenate tissue samples, as opposed to single-cell RNA-seq, which has distinct analytical considerations. Our pipeline is currently limited to only two of the various next generation sequencing analyses, and we would like to broaden the scope to also include DNA sequencing and other epigenetic sequencing protocols, such as
whole-genome bisulfite sequencing. Our platform can also be developed further to incorporate more advanced features, such as user interfaces for performing bioinformatics analyses from the web browser, login systems for users to keep track of their own progress, and forums and messaging systems for community feedback. We would also like to translate the pipeline into other languages to broaden its scope. In subsequent improvements, we plan to make the pipeline easily individualized for a user’s own data sources by adjusting SraRunTables. Future hackathons may offer a useful setting to further improve this developing resource. Despite these limitations, SeqAcademy provides a solid starting foundation for beginners to learn the fundamentals.

**Summary**
We have presented a novel, standalone educational tool for two types of next generation sequencing data: RNA-Seq and

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**Figure 2a. Principal component analysis (PCA) of yeast.** PCA suggests gene expression for euploid yeast samples (haploid) clusters distinctly from that of the aneuploid yeast samples (diploid chromosome X). The first two Principal Components account for ~70% of the variance in expressed genes). Data provided by Mulla et al., 2017.

**Table 1. Example RNA-Seq input.** This data presents the RNA-Seq data used in this tutorial. This tutorial observes RNA-Seq data of aneuploidy in yeast.

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**Table 2. Example ChIP-Seq input.** This data presents the ChIP-Seq data used in this tutorial. This tutorial observes ChIP-Seq data of induction by 3-AT in yeast.
Figure 2b. Volcano plot of differentially expressed genes between euploid yeast colonies versus aneuploid yeast colonies. The x-axis represents the difference in gene expression between the conditions. False discovery rate (FDR), a method for controlling for multiple testing, is along the y-axis. Each point represents a tested gene (N=3,926). Red points are those reaching genome-wide significance (at FDR<0.05, N=663), whereas grey points are genes not reaching statistical significance (FDR>0.05, N=3,263). Data provided by Mulla et al., 2017.

Figure 2c. Relative enrichment of chromosome X for differentially expressed genes. The relative enrichment of chrX for differentially expressed genes suggests the downstream results of this processing pipeline are consistent with biological expectations. The RNA-seq experiment was performed on yeast colonies with an extra chromosome X. Data provided by Mulla et al., 2017.

Figure 3. Distribution of intersected peaks across the yeast genome. This IGV screenshot shows in the bottom row the intersected peaks between the two treatment conditions of the yeast samples. The matching genes with each intersected peak can be analyzed. Data provided by Rawal et al., 2018.
ChIP-Seq data. This project offers a simple guidebook to an introductory analysis pipeline used in RNA-Seq and ChIP-Seq data. We introduced a cutting-edge bioinformatics tools frequently used for the acquisition, alignment, processing, analysis, and visualization of large-scale sequencing data and referenced further resources for continued learning. SeqAcademy meets the need for an educational analysis pipeline which can be used to teach undergraduate and graduate students with limited bioinformatics experience how to analyze publically available sequencing data.

Data availability
Use case data is available for the NCBI Sequence Read Archive Run Selector under accession numbers – SRP132584 and SRP106028

Software availability
Archived source code as at time of publication: https://doi.org/10.5281/zenodo.1233661 (Ather et al., 2018)

The code for this project is deposited under an MIT License on GitHub: https://github.com/NCBI-Hackathons/seqacademy

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References


This article presents a streamlined tool aimed toward novice bioinformaticians who wish to analyze RNA-Seq or ChIP-Seq data in one simple tool. The premise for this tool is excellent. Investigators who are new to these approaches often find the analysis of data daunting and are unsure of the tools to use for each step. SeqAcademy provides a single tool for all the steps in an easy to download package. Given that the target for this tool is investigators who do not have extensive expertise in the tools and analyses available, the article would benefit from more detailed descriptions of some individual components. Specifically, the following:

1. Alignment: The rationale for use of HISAT2 is clearly described. The time needed for this step should be discussed and, if possible, it would be helpful to provide an alternate local tool that could be used if users are unable to maintain consistent internet connectivity over the time needed for alignment completion.
2. RNA-Seq: A critical piece of RNA-Seq analyses are the statistical tools used to define differential expression. Some brief discussion of important cut-offs would be helpful.
3. Most tools incorporated into the package are described in 1-2 sentences. This should be consistent throughout, including for HTSeq, DESeq2.

The tool is really quite useful and I believe will be very valuable to novice investigators and students learning the pipeline of RNA-Seq or ChIP-Seq. Given that, it would be very helpful to provide more, not less, explanation of some of the basic tools such that the educational goal of this package will be served.

Is the rationale for developing the new software tool clearly explained?  Yes
Is the description of the software tool technically sound?  Yes
Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?  Yes
Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?  Yes
Yes

Are the conclusions about the tool and its performance adequately supported by the findings presented in the article?
Yes

**Competing Interests:** No competing interests were disclosed.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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Philip Ewels
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Bioinformatics training is of critical importance for the field of genomics, especially given the current shortage of experienced bioinformaticians and the utility of cross-training lab scientists in data analysis. In this manuscript, the authors describe a training tool developed to help teach people new to bioinformatics how to handle data from RNA and ChIP high throughput sequencing experiments.

Such a tool is valuable to the genomics community - it is a resource for interested parties to use in their own time and could also be very useful for those designing bioinformatics courses.

### Manuscript

The manuscript does a good job of describing the resource, as well as the reason it is helpful. In my opinion, it is longer than needed - the Introduction could be more concise and the *Use cases* section would feel more natural in the introduction. The figures could also easily be condensed into one and the table be a supplementary figure. Making the manuscript shorter would make it more accessible.

### Tutorial

The authors take an excellent approach to the design of their tutorial, using a Jupyter notebook and software installations from bioconda. These are appropriate, user friendly and provide an excellent starting point for well documented and reproducible analyses. Some dependencies are required, but these are well described on the tool's homepage and commonly used in bioinformatics. I attempted to run the tutorial on my laptop, but I ran into a few issues that required some debugging.

**Broken steps**

I came across a couple of problems in the notebook: I couldn't get the MultiQC commands to work - the mix of Python variables in the bash commands failed in my Jupyter notebook. I changed the command to use the following command:

```
!multiqc test/* --quiet --outdir test/multiqc_rnaseq --force
```

Next, the Bedtools steps didn't work - the intersect command refers to a sample SRR6703663, which
does not seem to be included anywhere in the tutorial before this point. I gave up at this point, so I'm not sure about the final steps. If the authors think that I did something wrong, I'd be happy to have another go.

I recommend trying to get some colleagues to run this tutorial from scratch to get more feedback.

**External scripts**
My main concern with the tutorial is that much of the downstream processing is done within R scripts outside of the Jupyter notebook. For me, this sort of misses the point - it would be preferable to have this code mixed in with the tutorial without any external scripts. It should be possible to have both Python (bash) and R in the same notebook, and this would make those steps part of the exercise rather than an abstract “runDeseq.R” script that requires the user to go and find and read through.

**Data subsampling**
Although the authors have endeavoured to use a small dataset (Yeast, not Human), the data used is still large. The authors note in the tutorial that the alignment “will most likely take several hours.”, which limits the utility of the tutorial in any teaching scenario.

It should be quite easy to use the `-u/-qupto` flag in HiSAT2 to limit the number of alignments performed. I imagine that most of the downstream analysis will still work with subsampled data, and will run much faster. I tried doing this with 1,000,000 reads and the alignment step completed in a couple of minutes.

### Tutorial - Minor points

**Software requirements**
I had trouble getting the bioconda installation command to first install and then activate inside the the notebook. I would instead recommend creating the conda environment on the terminal first (including jupyter as a package to install), activating it and then running jupyter. This is what I ended up doing to get the tutorial to work.

**Streaming Input Data**
The approach of streaming data from the SRA for the alignment step is a little non-standard. The reasoning is described in the paper as helping to reduce the disk space footprint required for the analysis. Whilst its cool that this step works, I would argue that it lessens the value of the tutorial, as most bioinformatics projects can not use such a method. Starting with regular static FastQ files would be more typical and useful for future analyses. This would also allow the additional step of FastQC for raw data analysis, which is pretty typical for such pipelines. The downside of this is that it invalidates my above subsampling idea! But SRA data could still be streamed to FastQ files with a similar subsampling approach.

**Two-in-one analysis**
The analysis presented uses common alignment and quality control steps for both sets of data, before splitting into bespoke RNA and ChIP-seq analysis. I see the reasoning for this but I think this complicates issues a little for users. Personally, I would prefer to see two separate Jupyter notebooks and separate analyses for the two different data types to avoid confusing the two. This would simplify future expansion of the resource across additional data types, which may not be able to share such analysis steps.

**MultiQC reporting**
The Quality Control step using MultiQC is placed after the HiSAT2 alignment. It would be better placed at the end of the analysis, as MultiQC also supports outputs from MACS, HTSeq and deepTools. A more
complete report would be generated if it were run with all of these outputs.

### Conclusions
I think that the aim of this paper is worthwhile and the approach is very nice. The tutorial itself feels a little unpolished and could do with a few trial runs on willing volunteers to iron out the issues I encountered. With a few tweaks and the changes above, I think that this tutorial could be the beginning of an excellent resource for budding bioinformaticians and educators.

**Is the rationale for developing the new software tool clearly explained?**
Yes

**Is the description of the software tool technically sound?**
Yes

**Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?**
Yes

**Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?**
Yes

**Are the conclusions about the tool and its performance adequately supported by the findings presented in the article?**
Partly

*Competing Interests:* No competing interests were disclosed.

I have read this submission. I believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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